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Supernovae

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Abstract. Supernovae are intimately entwined with virtually all areas of astronomical research from the metal content of solar system bodies, to feedback into star formation, to the production of gravitational waves. Here I will briefly review the observational properties and explanatory models of supernovae, and I will then highlight some recent results that have helped to better constrain the physical understanding of these stellar explosions. The latter portion will be strongly biased toward the Texas Supernova Search sample, which has gathered detailed observations of the normal (Type Ia SNe: 2005cg, 2005hj, 2006X; Type II SN: 2006bp) and the extraordinary (SNe 2005ap and 2006gy) among others.

1. Introduction

Supernovae are stellar explosions so catastrophic that in a brief period (seconds to days) all of a star's remaining fuel is consumed and/or expelled leaving behind a compact object, such as a neutron star or a black hole, or, in other cases, nothing but an expanding shell of gas. The glow of the cooling ashes may be augmented by the decay of radioactive species synthesized in the explosion or through interactions with circumstellar gas and last for months or years. A star's fate is essentially sealed at creation by its birth weight, metallicity, and by the presence of any companions close enough for interactions. Solitary stars that initially weigh in at $\sim$7-8 $M_{\odot}$ will eventually lose their extended hydrogen envelopes to expose their degenerate cores. With interior temperatures too low to continue nuclear burning and lacking external stimuli, the core will simply cool down and fade over time. The initial mass upper limit for production of such white dwarf (WD) stars is derived from stellar evolution codes, and the range reflects both uncertainties in the codes and the effects of metallicity (e.g. Eldridge & Tout 2004). If the star is initially more massive than this limit, so that it may burn carbon and later heavier elements up to iron, or if it interacts with a companion, an explosive end is possible.

Observationally, supernovae (SNe) are classified primarily by their spectral features and, in some cases, secondarily by their photometric evolution (see Filippenko 1997 for a review). In brief, SNe with (obvious) hydrogen lines are classified as Type II, and this class further breaks down into Types II-P, II-L, and IIn based on the presence of a photometric plateau (Patat et al. 1994), a linearly declining light curve, or narrow lines in the spectra, respectively. Supernovae without obvious hydrogen lines are classified as Type Ia (SNe Ia) if they show strong absorption around rest 6150 Å (usually associated with the blue shifted Si II λ 6355 doublet), or Type Ib if this feature is lacking but strong He lines are present. All remaining supernovae are classified as Type Ic. There are also hybrid objects such as the "Type IIb" SN 1993J, which initially resemble a particular class (e.g. Type II) but later transition to another (Type Ib). Given the qualitative and vague definitions delineated above, SNe are often compared to archetypal examples via χ^2 fits or cross correlation and labeled in accordance with the best match (e.g. a "1999aa-like Type Ia").

Theoretically, SNe are grouped into one of three explosion classes: thermonuclear, core-collapse, or pair-instability. The most massive stars, especially first generation stars from the early universe, are thought to explode through the pair-instability mechanism (Barkat et al. 1967; Fraley 1968), although the lower mass limit is poorly understood and highly sensitive to metallicity. In such events the interior photons, which provide the pressure necessary to balance the crushing force of gravity, attain energies greater than the rest mass of an electron-positron pair. The loss of photons to pair production then lowers the adiabatic index below the critical $\gamma = 4/3$ value, and and the core will contract. Heger & Woosley (2002) postulate that above a given mass ($\sim 260\,M_\odot$), the core will not be halted and it will form a black hole. In the range $140\,M_\odot \leq M \leq 260\,M_\odot$, thermonuclear runaway will occur and the reaction will proceed to obliterate the star; however, at lower masses the result will instead be a large amplitude pulsation that will expel a significant fraction of the outer envelope before burning in the core is halted. In this latter case, the star will survive and may explode later through core collapse (Woosley et al. 2007).

Heger et al. (2003) have calculated the end points expected for isolated stars with various initial masses greater that $\sim 8\,M_\odot$ (note that these calculations neglect physical processes such as rotation, and most massive stars are expected to possess companions). Below (metal-free) initial masses of $\sim 140\,M_\odot$, Heger et al. (2003) find that these massive stars are doomed to explode as core collapse supernovae. In these events, the progenitor forms a dense Fe core through the usual burning cycle, which collapses under its own weight. The core rebounds from this collapse and unbinds the envelope, forming a supernova. The details of this process are still poorly understood, but they may involve neutrino interactions (Janka et al. 2006), shock instabilities (Blondin & Mezzacappa 2006), acoustic instabilities (Burrows et al. 2006), and magneto-rotational effects (Akiyama et al. 2003). Heger et al. (2003) show that low metallicity progenitors with higher initial masses ($> 25\,M_\odot$) will form black holes by direct collapse or through fall-back, while lighter stars will leave behind neutron stars. At metallicities near solar and higher, all massive progenitors form neutron stars. The observational classes Type II, Type Ib, and Type Ic all correspond to core collapse events. The differentiation being the extent of mass loss incurred prior to the ultimate explosion.

The remaining class of supernovae, the Type Ia events, are thought to be thermonuclear explosions of white dwarf stars (see Branch 1998; Hillebrandt & Niemeyer 2000). Except for a possible sub population of stars just below the core-collapse cutoff that may explode in solitude (the so-called "Type 1.5"; Han & Podsiadlowski 2006), low mass progenitors require interaction with an external body to explode. Possible scenarios include mass transfer from a main sequence or evolved companion onto a white dwarf via Roche Lobe overflow or a common envelope phase, and WD-WD mergers. Electron degeneracy pressure cannot support a star above the Chandrasekhar mass (about 1.4 $M_\odot$), so thermonuclear run away is triggered as accretion pushes the total mass toward this limit. The nature of the flame propagation has been debated, but delayed detonation models of C/O white dwarfs reasonably account for the observed properties of Type Ia SNe (Höflich et al. 2006).

Type Ia SNe are the best studied class of SNe owing to their bright peak luminosities (typically about -19.5 mag absolute), their small dispersion (~ 0.3 mag intrinsic, < 0.1 mag after corrections), and hence their utility as cosmological probes (Riess et al. 1998; Perlmutter et al. 1999). They comprise most, but not all, events observed to reach luminosities greater than about -19 mag. Type II supernovae show a much wider range of peak luminosities, with typical values of about -17.0 mag (Richardson et al. 2002). Type Ib and the spectroscopic default Type Ic SNe also show a range of peak magnitudes and light curve shapes, but the typical peak magnitude is $M_V \sim -18.1$ (Modjaz 2007).

2. The Texas Supernova Search

In order to obtain multi-epoch spectral observations of supernovae starting from the earliest possible phases, we began a search for optical transients with the 0.45-m ROTSE-IIIb telescope (Akerlof et al. 2003) in 2004. The Texas Supernova Search (TSS; Quimby 2006) covered the entire Virgo, Ursa Major, and Coma Galaxy clusters, and other select fields every 1-3 nights as weather and season allowed. This project was made technically feasible by ROTSE-IIIb's wide field of view ($1.85^\circ \times 1.85^\circ$), the large amount of telescope time available ($\sim 25\%$ of every night), and its fully robotic operation. Transient candidates were promptly uncovered with a modified version of the PSF-matched image subtraction developed by the Supernova Cosmology Project (Perlmutter et al. 1999), and image thumbnails were posted to the web for final vetting by human scanners. Candidates which passed all selection criteria (e.g. detected at $> 5\sigma$ significance, no significant motion between observations spaced by ~ 30 minutes, not matching a known variable source, etc.) were directed to the neighboring 9.2-m Hobby-Eberly Telescope (HET) for spectroscopic typing. This typically occurred the following night, although in some cases the spectra were acquired just hours after discovery (e.g. SN 2005hj). When weather or a lack of observing time precluded spectroscopic confirmation with the HET, we contacted other researchers directly or via IAU Circulars so that all supernova discovered by the TSS were spectroscopically confirmed.

From November 2004 through November 2007, we discovered or independently detected 30 supernovae, and we obtained multi-epoch spectral time series for several events. In the following sections, I will summarize some of our key findings and describe how these results and contemporary works have furthered our understanding of supernovae since the inception of the TSS.

3. Type Ia Supernovae

In this section I present three Type Ia SNe which were observed by ROTSE-III and the HET as part of the Texas Supernova Search. First reported by a Japanese amateur and the CROSS program (Ponticello et al. 2006), SN 2006X was a highly reddened event initially showing high velocity ejecta and later evolving Na I D lines. SN 2005cg is a completely typical Type Ia SN, and the

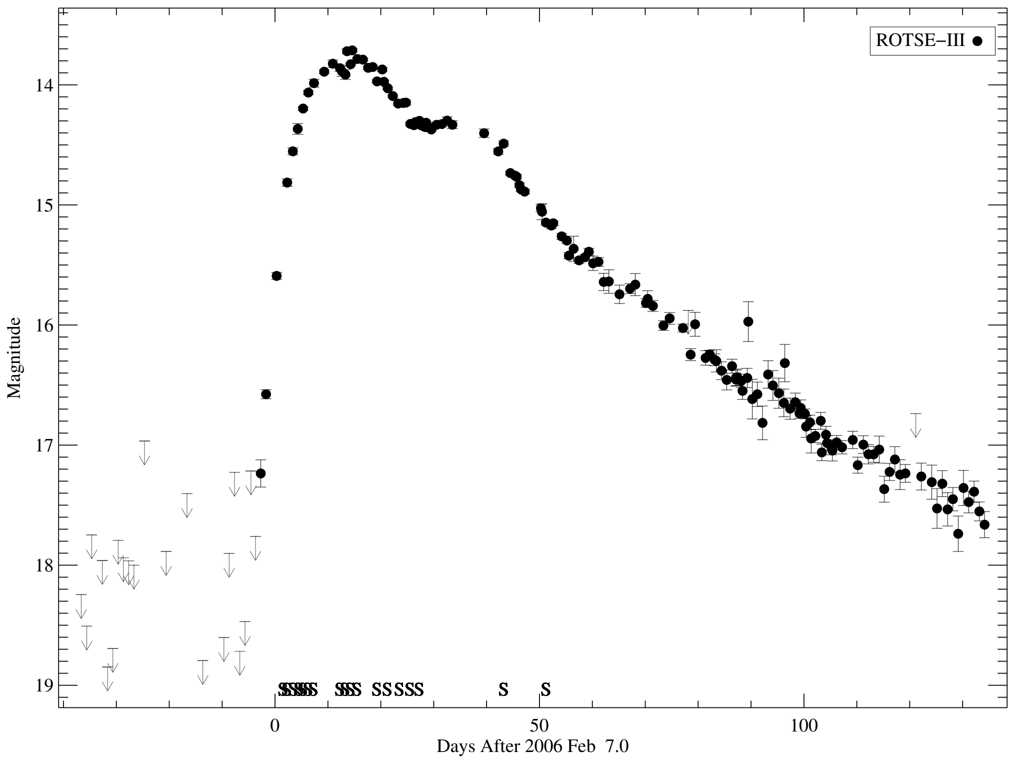

Figure 1. Preliminary ROTSE-III unfiltered light curve of the Type Ia supernova 2006X in M100. From Quimby (2006).

early spectra provide evidence for a detonation phase in such normal events. SN 2005hj may strictly be considered a normal Type Ia SN, however, multi-epoch HET observations provide evidence for shell interactions.

3.1. SN 2006X

The preliminary unfiltered ROTSE-III light curve of SN 2006X in the galaxy M100 is shown in Figure 1. We first detected the supernova on 2006 Feb 4.29 UT at about 17.2 mag. Observation upper limits from the previous nights show this was soon after explosion, and the SN brightened by more than 3 mag in the following nights to its peak of about 13.8 mag. A second maximum is seen about 25 days after this principle peak, as is commonly seen in the R-band and redder wavelengths (see Kasen 2006). Early spectral typing by the HET (Quimby et al. 2006a) revealed an unusually red continuum with rapidly expanding ejecta, and strong polarization (Wang et al. 2006).

High resolution spectral observations of SN 2006X obtained over multiple nights reveal changes in the narrow Na I D lines (Patat et al. 2007b). This is the first Type Ia SN with a published high resolution spectral time series. Such variations are not seen in other lines, such as Ca II H&K. Patat et al. (2007b) argue that the variability in the Na I D lines is a sign of circumstellar interaction with a pre-supernova wind and they use the derived wind velocity to classify the companion star as a red-giant. Similar observations have now

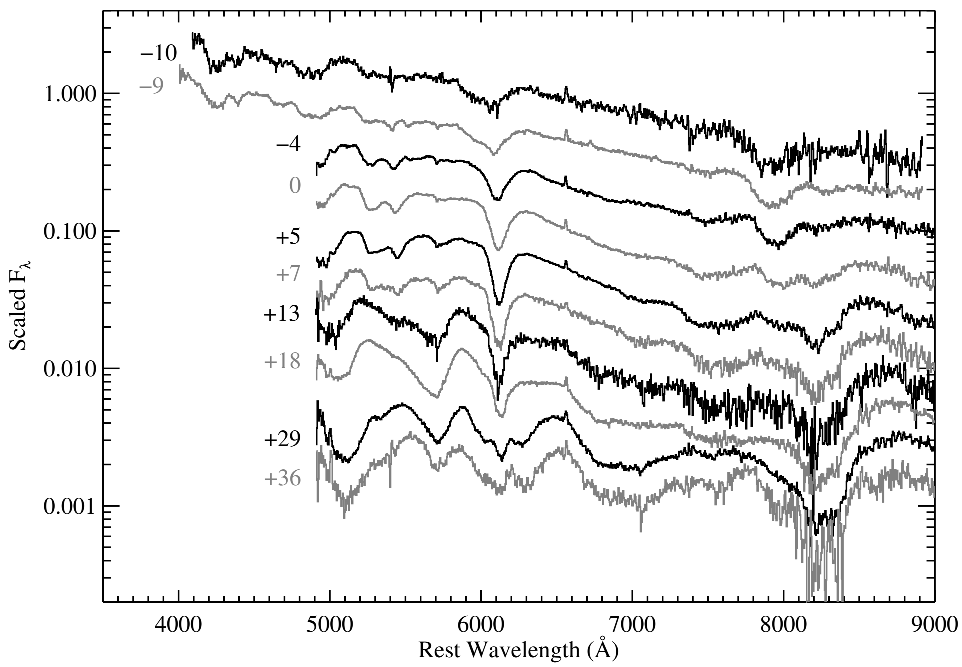

Figure 2. Spectral evolution of SN 2005cg as captured by the HET. From Quimby et al. (2006b).

been published for additional Type Ia SN. No variations are seen in the Na I D lines of SN 2007af (Simon et al. 2007) nor SN 2000cx (Patat et al. 2007a), which implies differing progenitor systems or non-spherical geometries with preferred viewing angles.

3.2. SN 2005cg

SN 2005cg eventually proved to be a completely normal Type Ia event; however, this was far from clear at the onset. The first spectrum taken by the HET revealed a Si II '6150' P-Cygni profile with what seemed to be an unusual absorption trough extending far into the blue (top spectrum in figure 2). A high velocity Ca II IR triplet feature was also clearly detected. As the supernova evolved, the light curve showed the initial spectrum was a rare, 10 day prior to maximum light observation, and the spectra taken around maximum were rather ordinary. In Quimby et al. (2006b), we suggest the presence of Si, a burning product, at high velocities is incompatible with deflagration models since the subsonic flame cannot burn through these expanding outer layers. Instead, we suggest normal Type Ia SNe, such as 2005cg, are marked by a detonation phase.

Noting that the blue wing of the Si II absorption cuts off abruptly as it meets with the continuum, and that this cutoff further corresponds to the minimum of the high velocity Ca II IR feature, we further suggest the observations are consistent with a shell interaction. Gerardy et al. (2004) claim that a solar gas mixture in the immediate vicinity of the explosion, possibly in the form of a thick accretion disk, can account for the high velocity Ca II IR feature regularly observed in Type Ia SNe at early times, and they predict such material would

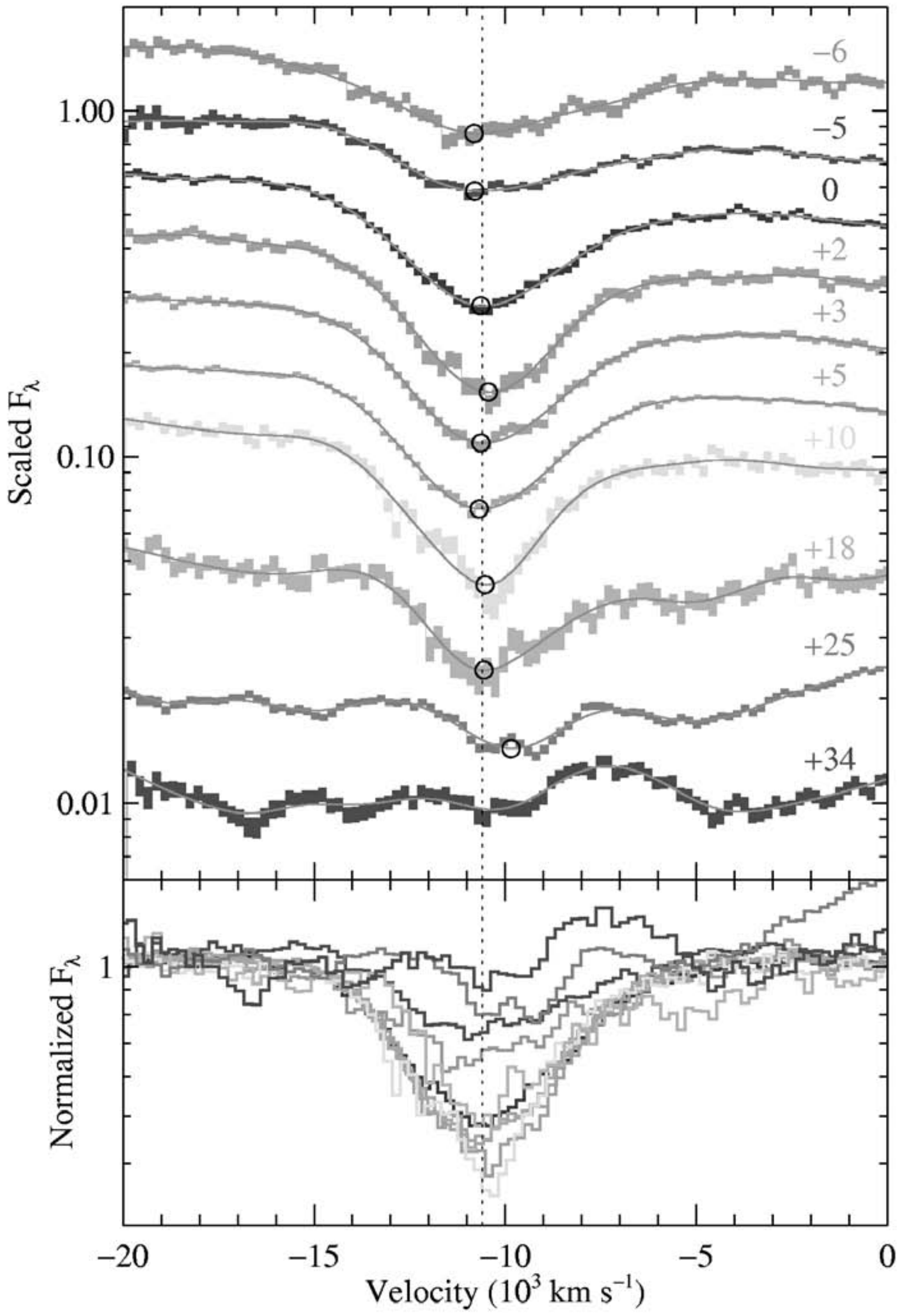

Figure 3. Spectral evolution of the Si II '6150' feature in SN 2005hj as recorded by the HET. From Quimby et al. (2007a).

truncate the velocity distribution of the highest velocity layers, much as we observe for SN 2005cg.

3.3. SN 2005hj

Much like the case of SN 2005cg, our early HET spectra of SN 2005hj showed an unusual Si II line profile and we pursued a multi-epoch spectroscopic follow-up campaign. In this case, the feature was unusually shallow and not particularly extended in the blue despite the early phase of the initial spectra. Continued monitoring over the next few weeks revealed little variation in the line until the photosphere receded below the Si layer and the Fe lines began to appear. In Quimby et al. (2007a), we find that the minimum of the Si II line, a proxy for the photospheric velocity, remains essentially constant at $10\,600 \pm 150\,\mathrm{km\,s^{-1}}$ between maximum light and +18 days (Fig. 3). We take this as a sign that the photosphere is hung up in a dense shell over this period, as could form in a pulsation delayed detonation model or in a double degenerate merger. Although SN 2005hj is technically a normal-bright (or core-normal; Branch et al. 2006) Type Ia SN, the presence of this velocity plateau is in contrast to the smooth deceleration of $1\,000\,\mathrm{km\,s^{-1}}$ or more exhibited by other normal Type Ia SNe (see Benetti et al. 2005). Thus there may be different progenitors or different explosion modes within the observed population of normal Type Ia SNe.

4. Type II Supernovae

Type II SNe, or explosions of stars with sufficient H in their envelopes to produce obvious spectral lines, are often dimmer than their Type Ia SN cousins but more prevalent in the cumulative history of the universe. In this section I will discuss the ordinary, if not unusually well observed, SN 2006bp, and the two most luminous supernovae ever identified, SNe 2006gy and 2005ap.

4.1. SN 2006bp

This Type II-P supernova was discovered by K. Itagaki of Yamagata, Japan (Nakano & Itagaki 2006). We detected SN 2006bp with ROTSE-IIIb on 2006 April 9.15 at an unfiltered magnitude of 17.75 ± 0.19 (Quimby et al. 2007c). Null detections from the previous nights and the steep initial rise (Fig. 4) indicate that the supernova was caught soon after shock breakout. Non-LTE modeling with the CMFGEN code indicates that the shock breakout date is 2005 April 7.9 ± 0.4 (Dessart et al. 2007). The light curve shows a clear plateau phase lasting $\sim$ 100 days, defined roughly as lasting from the midpoint of the sudden rise to the midpoint of the rapid fading prior to the exponential decay tail. The average decline rate between days +121 and +335 in this unfiltered data is $0.0073\,\mathrm{mag\,day^{-1}}$, which is significantly slower than the $0.0098\,\mathrm{mag\,day^{-1}}$ decline expected from the decay of ^{56}Co, and this may suggest an additional source of energy production sustaining the luminosity.

The first spectra obtained for SN 2006bp are most notable for their mainly featureless, blue continua. Close inspection of the data, however, reveals several broad P-Cygni profiles which we identify as Hα, He I λ5876, and He II λ4686. This is the first time such broad He II has been seen in the spectra of a supernova. More intriguing still are several narrow emission features present in the April 11 data, but absent on April 12. We conclude these lines originate from highly ionized He and C atoms in the vicinity of the explosion–by April 12 the SN

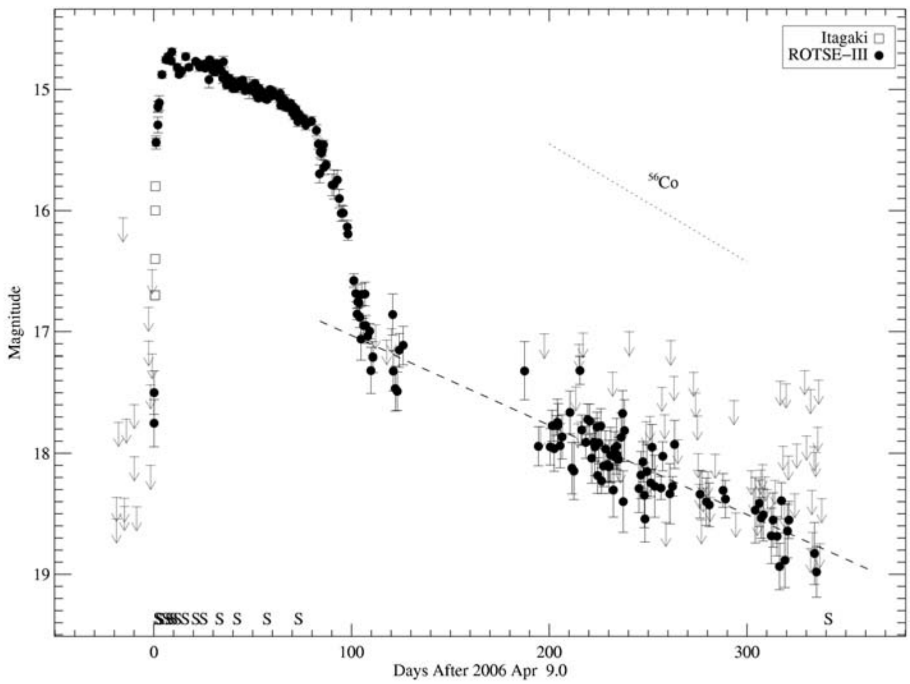

Figure 4. ROTSE-IIIb unfiltered light curve of SN 2006bp. From Quimby et al. (2007c).

ejecta have over taken this material thus squelching their narrow lines. These could be the outer layers of the progenitor itself.

At later times, the presence of "notches" to the blue of prominent P-Cygni profiles (Hα, Na I) is intriguing in its own right. Previous studies have explained these features as arising from metals such as N (Dessart & Hillier 2005). However, for SN 2006bp these features do not shift red with time in pace with other lines. In (Quimby et al. 2007c) we argue that this and other observations may signal a line forming region in higher velocity layers above the photosphere.

4.2. SN 2006gy

SN 2006gy was found near the core of NGC 1260, and there was some early speculation that it was not a supernova at all but rather an AGN. However, adaptive optic observations would eventually confirm SN 2006gy's separation from the galaxy core, and thus verify it as a supernova (Ofek et al. 2007; Smith et al. 2007). When first detected by ROTSE-IIIb, the apparent magnitude and cataloged distance to the host suggested a luminosity somewhat brighter than a Type Ia SN around maximum light. However, optical spectra indicated strong absorption along the line of sight, partially from our Galaxy but mainly from within the host (Prieto et al. 2006). After correction for this absorption the peak luminosity was corrected to an unprecedented -22 mag absolute. Smith et al. (2007) show SN 2006gy took ~ 70 days to reach its maximum brightness and that it stayed brighter than -21 mag for 100 days.

Although it is not yet clear what produced such a luminous and slowly evolving supernova as 2006gy, the available lines of evidence all point to an explosion of a massive star (Smith et al. 2007). It is at least possible that SN 2006gy was a pair instability event, which makes it the first observed supernova for which such a scenario must be considered.

4.3. SN 2005ap

Although it was found long before SN 2006gy, it was not confirmed until later that SN 2005ap was actually more luminous and in fact the brightest supernova ever observed after correcting for distance (Quimby et al. 2007b). SN 2005ap was found by ROTSE-IIIb in the Coma Cluster fields, but it is actually located well behind the cluster. A spectrum obtained by the HET shortly after discovery showed a very blue continuum with a few broad but shallow absorption features and a single narrow emission line. This narrow line was located significantly to the blue of zero-velocity Hα. A second, higher S/N spectrum taken by Keck/LRIS about 10 days later confirmed this feature and revealed a weaker emission line just to the blue, which showed this was the O III $\lambda\lambda$4959,5007 doublet. The Keck data also showed an absorption doublet in the blue consistent with Mg II in the same rest frame. This securely places the redshift of SN 2005ap at $z = 0.283$, which sets the peak of the unfiltered light curve at a record breaking -22.7 mag absolute.

It is difficult to explain this extraordinary luminosity, which corresponds to about $10^{45}\,\mathrm{erg\,s^{-1}}$ after an approximate bolometric correction, in the context of a supernova explosion. Yet the data are most consistent with a supernova. One possibility is that the engine powering SN 2005ap is similar to the engine of a gamma-ray burster, but in this case the H envelope (required by the detection of an Hα P-Cygni profile in the spectra) swallows the gamma-ray light. As suggested by Young et al. (2005), the bright subclass of Type II-L supernova may reflect such a progenitor, with the energy of the gamma-ray burst-style engine depositing a large amount of energy in the H envelope.

5. Concluding Remarks

The Texas Supernova Search was successful in its designed goal of capturing early spectra of supernovae – in fact our observations of SN 2006bp are the earliest ever obtained for a normal SNe – but the inclusion of the two most luminous supernovae ever identified in our small sample is, to say the least, unexpected. So how is it that a seemingly modest survey with a 0.45-m telescope produced such record-breaking discoveries? There are two possible avenues of explanation: 1) there is a unique aspect to the TSS that allowed these unique SNe to be found, or 2) it was complete luck. It is impossible to determine *a posteriori* if the second possibility is true especially since the detailed rates and environmental properties of SN 2005ap and/or SN 2006gy-like events are not yet known. On the other hand, there do appear to be several key differences between the TSS and other surveys that may naturally relate to the selection of such unusual SNe.

Figure 5 shows the redshift distribution of the first 30 SNe in the TSS sample including both SNe 2005ap and 2006gy. ROTSE-III is sensitive to the luminous Type Ia class out to a redshift of $z \sim 0.09$, and we found ~ 18 out to this limit. We only found one SN 2005ap-like event, however, at a redshift of $z = 0.28$, although we were sensitive to such events at closer distances. In other words our effective search volume for SN 2005ap-like events was ~ 3 times that of SNe Ia, but we found $1/18^{\text{th}}$ as many, so the rate of SN 2005ap-like events cannot be much larger than $\sim 1/50^{\text{th}}$ the Type Ia SNe rate. SN 2005ap-like events are thus rare, and the huge volume sampled by the TSS (comparable to all previous nearby searches) could be one key in their discovery. Also, since the spectral features of SN 2005ap are quite subtle, the high S/N spectral follow-up with the HET and Keck telescopes were critical to determining the distance and hence the intrinsic luminosity. Previous surveys that followed-up nearby SNe with smaller spectroscopic instruments or that found fainter SNe at greater distances may not have had the S/N required to make such a discovery.

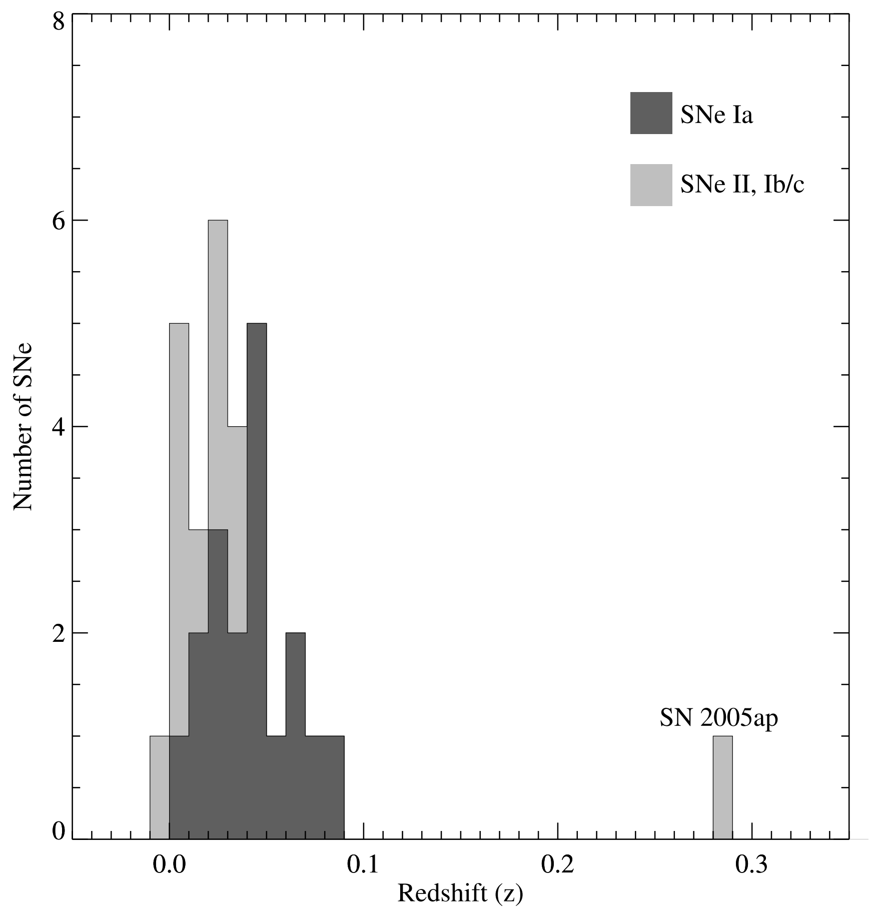

Figure 5. Redshift distribution of all supernovae in the Texas Supernova Search sample. From Quimby (2006).

For SN 2006gy, it is at least interesting that the first in a presumed class of SNe would be found near the core of a galaxy since the TSS was perhaps the first survey sensitive to so-located transients. The Lick Observatory Supernova Search, for example, observed NGC 1260 four times before ROTSE-IIIb in the summer of 2006, and it detected SN 2006gy first in the process. However the larger aperture and finer pixel scale of KAIT were rendered moot by software that automatically rejected SN candidates within 2.4″ of galaxy centers (W. Li, private communication 2007; see also Smith et al. 2007). As this is a common practice in transient searches, it is evident how SN 2006gy-like events could have been missed in the past if they prefer the cores of galaxies. There is also some physical motivation as to why the explosions of such presumably massive events may prefer the cores of galaxies. As pointed out by Portegies Zwart & van den Heuvel (2007), the deep potential well in the cores of galaxies facilitates the generation of dense star clusters, and these may include some of the most massive stars in a given galaxy. It is at least worth considering that this previously unsearched environment holds some importance to the unusual properties of SN 2006gy, although there is as yet only one example of this "class" and a statistical sample would be needed to confirm such speculation.

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